# A Multivariate Approach to Geochemical Distinction Between Tin-Specialized and Uranium-Specialized Granites of Southern Nova Scotia

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# A multivariate approach to geochemical distinction between tin-specialized and uranium-specialized granites of southern Nova Scotia

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Like most granitoid bodies that host significant granophile deposits, the South Mountain batholith (SMB) of Nova Scotia consists of an earlier suite intruded by a later suite of smaller plutons that are more silicic and peraluminous. The latter generally show a range of other geochemical features that readily identify them as "specialized" and allow for their separation from the earlier "non-specialized" granites. In the case of mineralization associated with the SMB we can go one step further and clearly separate the specialized granites into stanniferous and uraniferous series, which can be identified even where no Sn or U enrichment is present. Although this can be done successfully using simple histograms of a number of elements (Li, P, Sn, and F), we show that combining all elements in discriminant analysis guarantees 100% success in separating the two groups. *R*-mode factor analysis aids in accounting for the variance within each group, the most important effect being a "biotite factor" because of both its magmatic role and its early breakdown by hydrothermal fluids. The stanniferous series is marked by what we call the "lithophile factor" (heavily loaded by $K_2O$, $P_2O_5$, Rb, F, Li, and W) and the uraniferous series by a "metallization factor" (loaded by Cu, Sn, Mn, and Zn). These can be interpreted in terms of dominantly magmatic processes for the former and dominantly hydrothermal processes for the latter. Furthermore, we emphasize that the separate suites do exhibit these independent characteristics even without mineralization being present.

Le batholite South Mountain (BSM) de la Nouvelle-Écosse, comme la plupart des corps granitoïdes renfermant des gisements granophiles significatifs, est formé d'une séquence antérieure pénétrée par une séquence postérieure composée de petits plutons plus siliceux et peralumineux. Ces derniers possèdent généralement une gamme de traits géochimiques qui permet de comprendre que ces plutons sont "spécialisés" et qu'on peut les distinguer des granites plus anciens "non-spécialisés." À propos de la minéralisation associée au BSM, nous pouvons en plus distinguer nettement dans les granites spécialisés une série stannifère et une série uranifère, lesquelles peuvent être identifiées même en l'absence d'un enrichissement en Sn ou en U. Bien que l'on puisse constater ces distinctions à l'aide de simples histogrammes d'un nombre d'éléments (Li, P, Sn et F), nous démontrons que si on combine tous ces éléments dans une analyse discriminante, la sépération de ces deux groupes est alors assurée à 100%. L'analyse factorielle mode-*R* aide à tenir compte de la variance à l'intérieur de chaque groupe, l'effet le plus important étant le "facteur biotite" à cause de son rôle dans le magmatisme et également de sa décomposition par les fluides hydrothermaux. La série stannifère est marquée par ce que nous appelons le "facteur lithophile" (coefficient de charge élevé dû à $K_2O$, $P_2O_5$, Rb, F, Li et W) et la série uranifère par un "facteur de métallisation" (coefficient de charge dû au Cu, Sn, Mn et Zn). La première série peut être interprétée en invoquant la prédominance des processus magmatiques et la seconde en termes d'une prédominance des processus hydrothermaux. En plus nous insistons sur le fait que ces séquences séparées montrent ces caractéristiques indépendantes même en l'absence de mineralisation.

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## Introduction

A fundamental assumption of economic geology is that there is a genetic and geochemical relation between deposit types and associated granitoid rocks. This concept of "specialized granites" (e.g., Tischendorf *et al.* 1978) is commonly used in exploration for such deposits, with certain element concentrations being taken as indicators of mineralization or potential for mineralization (e.g., Flinter *et al.* 1972; Tauson and Kozlov 1973; Hesp and Rigby 1973, 1974). In the case of "granophile deposits" (Strong 1981) such as Sn, W, U, Sb, they are characteristically linked to specialized granites that are muscovite-bearing and have a range of geochemical features as shown in Table 1. For example, they are typically peraluminous, high in $SiO_2$, Rb, F, Li, and Sn, and low in CaO, MgO, Ba, and Sr.

Although these features allow for the first-order recognition of specialized granites, there is generally less confidence in the ability to distinguish between those that are specialized for particular kinds of granophile deposits. It is the purpose of this paper to show that such distinctions can indeed be made between

TABLE 1. Average compositions, southern Nova Scotian (South Mountain batholith) and western European specialized granites

| | Nova Scotia tin-specialized granite (94 samples) | | | | | | | Nova Scotia uranium-specialized granite (136 samples) | | | | | | | Western Europe (after Tischendorf 1978) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\bar{X}$ | σ | $V$ | Cv (%) | Ku | Sk | 95% CI | $\bar{X}$ | σ | $V$ | Cv (%) | Ku | Sk | 95% CI | $\bar{X}$ | σ |
| $SiO_2$ (%) | 75.83 | 2.43 | 5.90 | 3 | 7.54 | −1.61 | 75.30–76.40 | 74.48 | 0.97 | 0.93 | 1 | 3.70 | −1.07 | 74.31–74.64 | 73.18 | 1.39 |
| $TiO_2$ | 0.13 | 0.12 | 0.01 | 90 | 71.50 | 8.03 | 0.11–0.15 | 0.08 | 0.01 | 0.00 | 20 | 5.91 | 1.59 | 0.80–0.09 | 0.16 | 0.10 |
| $Al_2O_3$ | 12.65 | 1.37 | 1.88 | 11 | 11.43 | 2.25 | 12.37–12.93 | 13.90 | 0.55 | 0.30 | 4 | 4.30 | 1.15 | 13.81–13.99 | 13.97 | 1.07 |
| $Fe_2O_3$(T) | 1.72 | 0.53 | 0.28 | 31 | 24.30 | 4.00 | 1.62–1.83 | 1.29 | 1.40 | 0.02 | 11 | 9.00 | 1 92 | 1.27–1.31 | — | — |
| FeO | 1.21 | 0.31 | 0.10 | 26 | 7.60 | 1.61 | 1.14–1.27 | 0.93 | 0.08 | 0.01 | 9 | 1.06 | −0.14 | 0.91–0.94 | 1.10 | 0.47 |
| MnO | 0.04 | 0.05 | 0.003 | 150 | 78.90 | 8.60 | 0.025–0.048 | 0.02 | 0.00 | 0.00 | 14 | 1.86 | 0.00 | 0.02–0.02 | 0.045 | 0.040 |
| MgO | 0.18 | 0.11 | 0.01 | 62 | 12.58 | 3.08 | 0.16–0.20 | 0.05 | 0.06 | 0.00 | 109 | 5.04 | 1.21 | 0.04–0.06 | 0.47 | 0.56 |
| CaO | 0.67 | 0.27 | 0.08 | 41 | 8.80 | 2.12 | 0.62–0.73 | 0.75 | 0.14 | 0.02 | 19 | 1.97 | 0.73 | 0.73–0.78 | 0.75 | 0.41 |
| $K_2O$ | 4.08 | 0.82 | 0.67 | 20 | 2.15 | −1.10 | 3.92–4.25 | 4.39 | 0.38 | 0.15 | 9 | 5.27 | 1.15 | 4.32–4.45 | 4.69 | 0.68 |
| $Na_2O$ | 3.41 | 0.83 | 0.69 | 24 | 8.05 | 0.95 | 3.24–3.58 | 3.48 | 0.27 | 0.07 | 8 | 6.60 | −1.47 | 3.43–3.52 | 3.20 | 0.61 |
| $H_2O^+$ | 0.76 | 0.23 | 0.05 | 31 | 8.52 | 2.08 | 0.71–0.81 | 0.63 | 0.13 | 0.02 | 21 | 0.85 | 0.74 | 0.60–0.65 | — | — |
| $H_2O^-$ | 0.02 | 0.02 | 0.001 | 140 | 1.15 | 1.36 | 0.01–0.02 | 0.03 | 0.04 | 0.00 | 156 | 4.66 | 1.99 | 0.02–0.04 | 0.18 | — |
| $P_2O_5$ | 0.11 | 0.03 | 0.001 | 26 | −0.61 | −0.10 | 0.10–0.12 | 0.44 | 0.04 | 0.00 | 10 | 2.05 | −0.04 | 0.43–0.45 | 0.20 | — |
| $CO_2$ | 0.12 | 1.42 | 0.02 | 116 | 45.00 | 6.09 | 0.09–0.15 | 0.07 | 0.04 | 0.00 | 60 | −0.23 | −0.04 | 0.06–0.07 | — | — |
| Ba (ppm) | 73 | 60.17 | 3 621 | 82 | 9.98 | 2.29 | 60–85 | 39 | 24 | 582 | 61 | 14.53 | 3.20 | 35–43 | — | — |
| Be | 14 | 7.10 | 50 | 52 | 29.49 | 4.52 | 12–15 | 8 | 4 | 12 | 44 | 36.30 | 4.95 | 7–9 | 13 | 5 |
| Cu | 7 | 26.00 | 690 | 405 | 62 70 | 7 58 | 1–11 | 1 | 25 | 646 | 83 | 2.06 | 1.14 | 26–36 | — | — |
| F | 3318 | 1042 | 108 665 | 31 | 0.26 | 0.17 | 3105–3532 | 4532 | 609 | 3709 | 13 | 0.72 | 0.35 | 4429–4636 | 3700 | 1500 |
| Li | 146 | 64 | 4104 | 43 | −0.51 | 0.10 | 133–159 | 517 | 48 | 228 | 9 | 1.76 | −0.51 | 508–525 | 400 | 200 |
| Mo | 2 | 0.05 | 0.31 | 30 | 1.96 | 0.33 | 1.72–1.95 | 1.4 | 0.61 | 0.3 | 38 | 2.70 | 1.04 | 13–1.5 | 4 | 2 |
| Pb | 7 | 4 | 18.0 | 61 | 2.60 | 1.30 | 6–8 | 5 | 3.61 | 13 | 77 | 3.52 | 1.14 | 4–5 | — | — |
| Rb | 700 | 122 | 14 973 | 17 | 5.30 | 0.20 | 675–725 | 760 | 63 | 390 | 8 | −0.514 | −0.05 | 758–779 | 580 | 200 |
| Sn | 50 | 60 | 3 715 | 120 | 12.40 | 3.20 | 37–63 | 39 | 8 | 70 | 22 | 0.66 | 0.29 | 38–40 | 40 | 20 |
| Sr | 31 | 112 | 153 | 40 | 5.58 | 1.67 | 28–33 | 38 | 13 | 160 | 33 | −0.17 | 0.51 | 36–40 | — | — |
| Th | 25 | 6 | 37 | 24 | 2.60 | 1.20 | 23–26 | 5 | 2 | 34 | 38 | 0.31 | 0.66 | 4.9–5.6 | — | — |
| U | 23 | 4 | 14 | 17 | 1.90 | 0.55 | 22–24 | 14 | 21 | 429 | 38 | 30.90 | 4.97 | 10–17 | — | — |
| W | 11 | 4 | 16 | 35 | 0.14 | −0.17 | 10–12 | 2 | 5 | 26 | 210 | −1.28 | −0.14 | 2–3 | 7 | 3 |
| Zn | 43 | 14 | 204 | 32 | 1.70 | 1.20 | 40–46 | 86 | 22 | 480 | 27 | 38.20 | 5.06 | 82–89 | — | — |

NOTES: $X$ = mean; $V$ = variance; Cv = coefficient of variation; Ku = kurtosis; Sk = skewness; CI = confidence interval; σ = standard deviation.

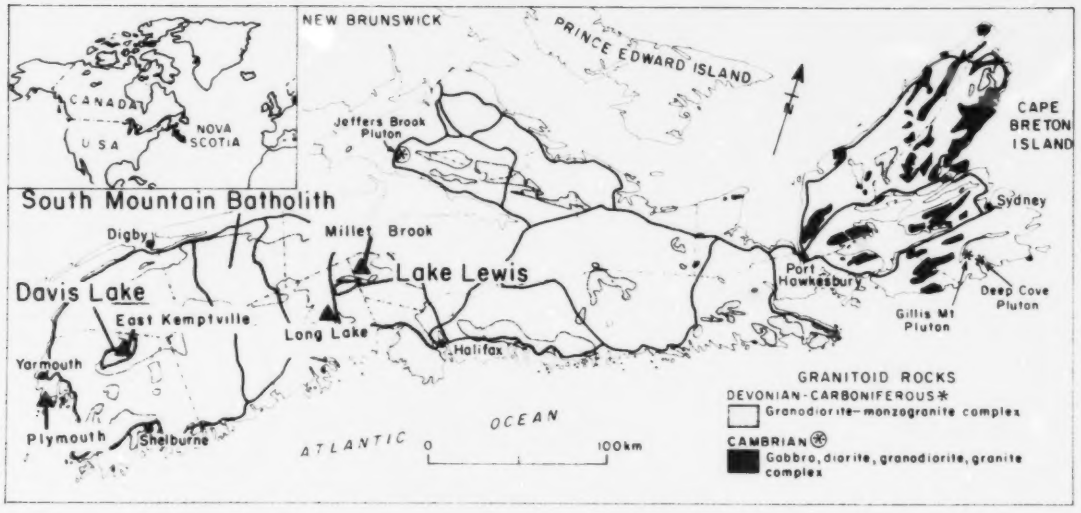


FIG. 1. Location of the Davis Lake (stanniferous) and Lewis Lake (uraniferous) plutons within the South Mountain batholith of Nova Scotia.

those specialized Devonian granitoids of southern Nova Scotia that contain uranium deposits and those that contain tin deposits.

## Geological setting and mineralization

The geological setting and petrogenesis of southern Nova Scotian granitoid rocks are generally well known from a number of recent papers (e.g., McKenzie and Clarke 1975; de Albuquerque 1979; Clarke and Halliday 1980; Longstaffe *et al.* 1980; Halliday *et al.* 1981; Muecke and Clarke 1981; Reynolds *et al.* 1981). Different aspects of their economic potential are discussed by Smith and Turek (1976), Chatterjee and Muecke (1982), Muecke and Chatterjee (1982), and Chatterjee (1980, 1982). Most known granophile mineral occurrences and deposits of southern Nova Scotia are associated with the South Mountain batholith (SMB), the large post-tectonic peraluminous granodiorite–granite complex that underlies much of southern Nova Scotia (Fig. 1).

The SMB intrudes deformed and metamorphosed sedimentary and volcanic rocks ranging in age from Cambro-Ordovician to Early Devonian (Emsian). Country-rock deformation and metamorphism are attributed to the Acadian Orogeny, which in this region has been dated at 415–400 Ma (Reynolds and Muecke 1978). Stratigraphic controls necessitate that the time of intrusion, crystallization, uplift, and erosion of the batholith be bracketed between Emsian and Tournaisian times. Recent Rb–Sr isochron studies (Clarke and Halliday 1980) give dates of 372–361 Ma to the various episodes of intrusion in the batholith and K–Ar $^{39}Ar/^{40}Ar$ dates (Reynolds *et al.* 1981) have a mean of 367 Ma.

Biotite granodiorite constitutes the earliest and most voluminous member of the batholith, into which were intruded a number of smaller bodies of biotite–muscovite monzogranite (including porphyry), leucocratic monzogranite, dykes and irregular bodies of aplite, and pegmatite. The principal types of uranium and tin mineralization recognized in the SMB are typified by the following examples.

The Millet Brook uranium deposit (Fig. 1) occurs in closely spaced en-échelon pods and lenses that are confined to northeast-trending shear and fracture zones in the 370 Ma biotite granodiorite that characterizes the early and least differentiated phase of the SMB. Where unaltered this phase consists of quartz, zoned plagioclase ($\approx An_{33}$), perthitic alkali feldspar ($\approx Or_{90}Ab_{10}$), biotite, muscovite, and accessory Mn-garnet, apatite, zircon, pyrite, pyrrhotite, ilmenite, and rutile. Alteration of these rocks, generally confined to within 30 m of the mineralized fractures, reflects potassic, sodic, calcic, and ferruginous varieties, producing secondary K-feldspar, albite, carbonate, biotite, muscovite, and chlorite. Chatterjee *et al.* (1982) have suggested that the formation of uranium mineralization was related to the late stages of felsic magmatism represented by leucomonzogranite, dykes of which are intersected in drill core at depth and found in the nearby Lewis Lake pluton. At Gaspereau Lake and East Dalhousie the uranium mineralization is found in shear zones, which are locally manganiferous, within leucomonzogranite.

The Sn–W–Cu–Mo mineralization at Davis Lake is restricted to greisen zones and greisenized granite within discrete bodies of leucomonzogranite. That of the East Kemptville deposit is associated with the

Davis Lake pluton (Fig. 1), essentially a leucocratic complex, including porphyritic muscovite–biotite granite, argillized and sericitized granite, albitized granite, and albitite. The porphyritic muscovite–biotite granite is characterized by phenocrysts of K-feldspar, but quartz phenocrysts are locally dominant. It otherwise consists of equal proportions of quartz, plagioclase, and perthite, with muscovite, biotite, fluorite, apatite, zircon, and rutile making up the remaining 5%. The argillized and sericitized granite is derived from generally similar rocks, but is not porphyritic and contains accessory topaz and cassiterite. The typical albitized granite is massive, sugary textured, free of mafic minerals, and locally cataclasized. Fluorite, topaz, and cassiterite are sparse, and some samples contain disseminated sphalerite, chalcopyrite, pyrite, pyrrhotite, and euclase. The albitites are leucocratic, coarse-grained, porphyritic, albite–quartz–muscovite rock. They contain small amounts of interstitial quartz, biotite, muscovite, phenakite, bertrandite, cassiterite, apatite, fluorite, and cryolite and are characterized by a complete absence of K-feldspar. The albitites locally grade into albite breccias.

## Geochemistry

This investigation is based on a systematic study of 230 samples, of which nine were collected from surface outcrops and the remaining 221 from diamond drill cores from the Davis Lake and Lewis Lake areas. The samples from the drill core (average length 20 cm) were sliced lengthwise: one half was subsampled for thin sections, polished sections, and permanent storage; the other half was cleaned thoroughly and powdered for chemical analysis.

The major-oxide analyses were done by using the analytical techniques of Abbey (1970), using a Jarrell-Ash 810 dual channel atomic absorption unit, except for $SiO_2$, which was determined colorimetrically using a lithium meta- and tetraborate fusion method.

The Rb, Ba, Sr, Be, Sn, and Mo contents were determined by non-volatile and volatile methods using a 3.4 m Ebert Jarrell-Ash grating spectrograph, and the intensities were measured on a 21300 Jarrell-Ash photodensitometer. The buffers for non-volatile and volatile methods were lithium carbonate, lithium fluoride, $K_2SO_4$, $Eu_2O_3$, and $PdI_2$, and $Al_2O_3 + BaCO_3$ and $KIO_4$, respectively. The limits of sensitivity are: Be, 3 ppm, Ba, 5 ppm; Sr, 3 ppm; Rb, 1 ppm; and Mo, 1 ppm. The Cu, Pb, Zn, and Li concentrations were determined by atomic absorption, with background correction applied for Pb, with limits of sensitivity less than 2 ppm.

Fluorine content of the samples was determined using a Fisher Accumet model 425 digital pH/ion meter. Samples (0.25 g) were fused with sodium carbonate – potassium nitrate (2:1) flux and dissolved in water. The solution was mixed with 50 mL of TISAB buffer and the fluorite concentration was measured with a specific ion electrode using the method of standard addition.

The U and Th contents of the rocks were determined using delayed neutron activation analysis by the Atomic Energy Commission of Canada. For uranium the samples were sealed in polyethylene capsules, stacked in the sample loader, and transferred pneumatically to the reactor for 60 s irradiation in a thermal neutron flux of approximately $10^{12}$ neutrons $cm^{-2}$ $s^{-1}$. The isotopes with short half lives were allowed to decay for 20 s, and the samples were counted for 60 s. The samples were compared with standards in which the uranium concentration is known from intralaboratory determination: DHG 1-1 (4.6 ppm), DHG 1-2 (18 ppm), BL 3-6 (35 ppm), Sy-3 (876 ppm).

Thorium content of the samples was determined using neutron activation followed by gamma spectrometry. The samples were irradiated for 2 h and after 7 days storage the 311.9 keV gamma peak of $^{233}Pa$ ($^{233}Th/^{233}Pa$) was measured using gamma spectrum measurement. Both the activation and measurement systems were calibrated using internationally recognized standards.

The precision of this major-element determination is generally better than 1% except for some elements in low concentration for which a precision better than 2% was obtained. The precision for minor and trace elements at levels below 0.1% is better than 10%. The accuracy of the determination was checked by comparison with Sy-2, Sy-3, and G-2 and the values obtained are within 2% of the recommended values (Abbey 1977; Flanagan 1973).

The geochemistry of the SMB is characterized by continuous linear variation trends from early- to late-stage rocks. McKenzie and Clarke (1975) suggested that the SMB consists of a "cogenetic suite" in which chemical trends are mainly controlled by fractional crystallization of plagioclase and biotite from a parental granodiorite magma. More recent trace-element work (Muecke and Clarke 1981) supports such a model, but emphasizes the importance of a fluid phase in determining chemical trends during the late stages of consolidation of the batholith. Chatterjee and Muecke (1982) attributed the occurrences of biotite leucogranite, argillized and sericitized granite, albitized granite, and albitite, as well as various types of greisen in the SMB to this fluid–rock or fluid–magma interaction. Chemical trends in these rocks are distinct and clearly diverge from those observed in the cogenetic suite, and Chatterjee and Muecke (1982) have grouped these rocks into what they term the "para-intrusive (specialized) suite." This para-intrusive suite can be separated from the cogenetic (non-specialized) suite by a number of elements, as exemplified by the Rb–$K_2O$ plot in Fig. 2.

Geochemical characteristics within the para-intrusive

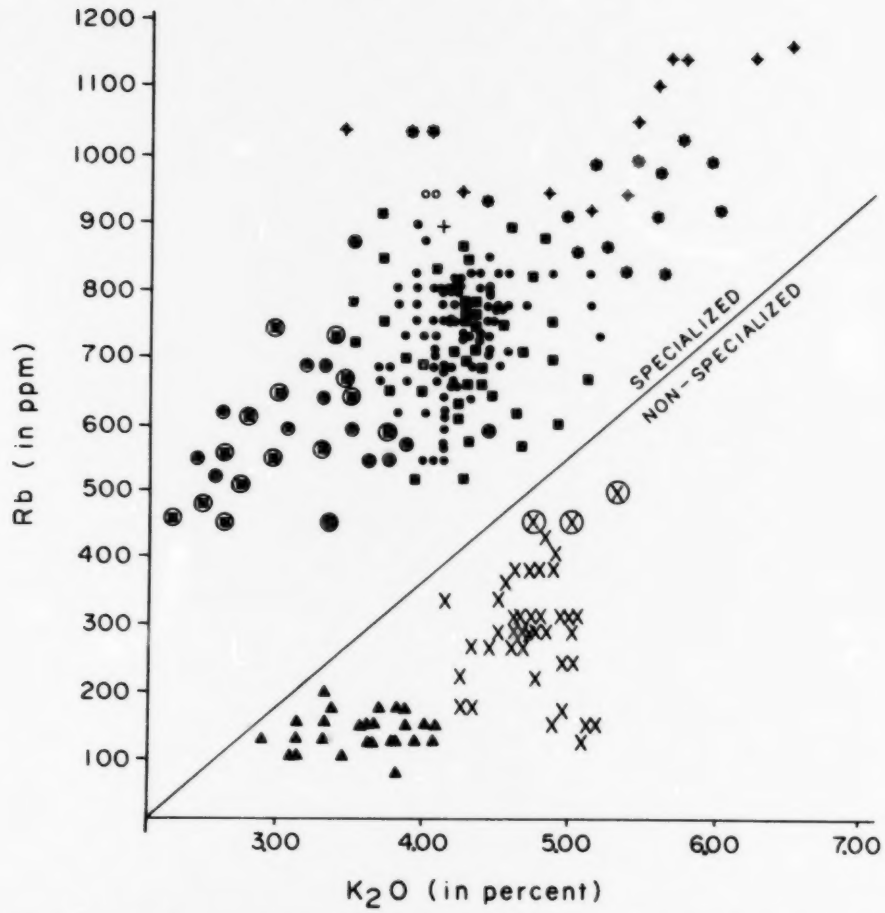


FIG. 2. Variation in K and Rb in the *specialized* and *non-specialized* granitoid rocks of Nova Scotia. Symbols as follows: ▲ granodiorite; × monzogranite; ⊗ aplite; ● uraniferous leucomonzogranite; ⊙ uraniferous albitized leucomonzogranite; ◆ uraniferous greisenized granite; ■ stanniferous leucomonzogranite; ◉ stanniferous albitized leucomonzogranite; ◈ stanniferous greisenized leucogranite.

suite can be compared in Table 1, where average compositions and other statistics are given for 136 samples of the uraniferous and 94 samples of the stanniferous granitoids. It can be seen from Table 1 that the two groups have similar concentrations of major elements, and that they are also similar to the specialized Hercynian granitoids of western Europe. However, there are a number of significant differences in trace-element concentrations that are worthy of examination for both theoretical and practical reasons.

Figure 3 highlights some of the advantages and disadvantages of using histograms to separate the uraniferous and stanniferous suites in Nova Scotia. The unimodal plots of $K_2O$, Rb, Zn, and Sn emphasize that, although there are differences in means and variances given by the statistics, and there is a hint of bimodality for Zn and Sn, the two suites could not be separated without their a priori recognition. On the other hand, the histograms for U, Li, $P_2O_5$, and Th are strongly bimodal, leaving no doubt as to the presence of two separate populations.

Although it thus seems that straightforward histograms for some elements can be used to separate these two populations, there is no a priori basis to choose which elements to use, and it would clearly be of some advantage to evaluate the full body of data. This can best be done by assessment in terms of multivariate statistics, and we have chosen two approaches, discriminant analysis and factor analysis, both of which are well described in the literature (e.g., Koch and Link 1971; Klovan 1975).

### *Discriminant analysis*

Discriminant analysis is a statistical procedure aimed

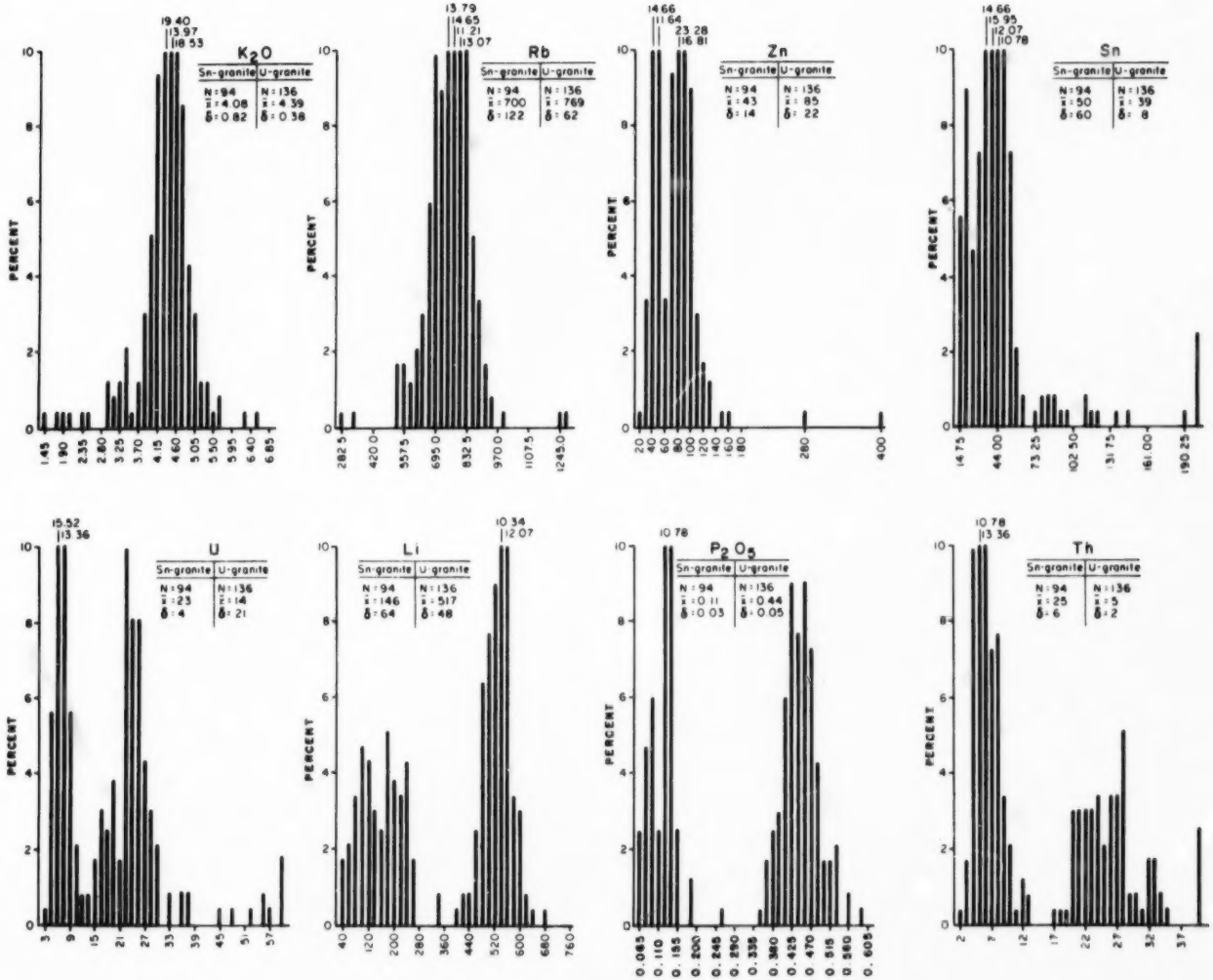


FIG. 3. Histograms of trace-element concentrations in the 230 samples of granitoid rocks from the South Mountain batholith of Nova Scotia. Note that the highest class interval for Sn contains all concentrations above 200 ppm, for U above 60 ppm, and for Th above 40 ppm. The numbers of histogram peaks give the percentages of samples within these class intervals.

at distinguishing between two or more classes of objects by developing a rule, or "discriminant function" ($L$), based on measurements (variables) obtained on each sample in order to develop a linear combination $L$ of variables ($SiO_2$, $TiO_2$, ..., U, Th, etc.). For example $L = \alpha_1 SiO_2 + \alpha_2 TiO_2$, ..., etc., where values for $\alpha$ are chosen to provide maximum discrimination between the two populations. Clearly, for effective discrimination between two groups, variations in the value of $L$ for samples within a group must be significantly less than the differences in $L$ between the two groups. Once the values of $\alpha$ are obtained for each variable, $L$ can be calculated for individual samples, and the two populations can then be evaluated in terms of this single function, $L$. The validity, or significance, of the discrimination can be estimated by a number of measures. One is the relative percentage of eigenvalues (the sum of the eigenvalues is a measure of the total variance existing in the discriminating variables) and the other is the canonical correlation (a measure of association between the single discriminant function and the variables that define the group membership).

The discriminant function calculated from the 94 stanniferous and 136 uraniferous Nova Scotia granites required only 12 variables (four oxides and eight trace elements) for 100% separation of the two groups. This function is as follows:

$$\begin{aligned} L = {} & 0.1325Fe_2O3(T) - 0.5465FeO + 0.2698K_2O \\ & + 0.6896P_2O_5 - 0.3356Be + 0.9194Li \\ & + 0.1087Pb - 0.4621Rb - 0.4241Th \\ & + 0.1481U - 0.2658W + 0.1914Zn \end{aligned}$$

It can be seen from Fig. 4 that there is substantially less variation of $L$ within each group than there is between the groups, and that they are completely separated without overlap. This is a significant improvement on even the most distinctive histograms for specific elements shown in Fig. 3.

*Factor analysis*

*R*-mode factor analysis is a technique that attempts to explain the relationships among many variables in terms of a few conceptually meaningful, relatively independent factors. In simple terms a factor $F$ is a weighted linear combination of the original variables:

$$F = \sum_{j=1}^{p} W_j X_j = W_1 X_1 + W_2 W_2, \ldots, W_p X_p$$

where $W$ is a factor weight (to determine the factor score for a given variable) and $X$ is the variable. Thus, factor analysis reduces the number of measurements needed to describe a phenomenon, and because this is related to geological aspects the interpretation of the factors is largely non-statistical and useful to gain some insight into the geochemical similarities and differences between the stanniferous and uraniferous granites of southern Nova Scotia.

The principal factors provide information on variables that account for the variance within each data set and may reflect differences in mineralogy, alteration type, mineralization, etc. Figure 5 summarizes the four principal factors that were calculated for each data set after log-normalization to eliminate the effects of strongly skewed element distributions. They cumulatively account for 71% of the variance in the stanniferous granites and 64% of the variance in the uraniferous granites. Low factor loadings ($<0.25$) have been omitted for the sake of clarity. Similarities between the two types of granite are reflected in the fact that three of the four principal factors are similar for both data sets. A fourth factor is, however, distinctly different and provides some insight into the processes that may have led to the diverse types of mineralization.

The most important factor for both sample sets (1A, 1B) is heavily loaded with respect to Fe (total), FeO, and Li and to a lesser degree MnO, MgO, $TiO_2$, Rb, and Sn. We interpret this as a "biotite" factor, since biotite is typically the major carrier of Li, Rb, and Sn in granitoid rocks (Beus 1964; Foldvari-Vogel 1978). The high variance that is accounted for by this biotite factor may reflect primary variations in the modal biotite content of the two suites and (or) enhanced mobility of the elements present in the biotites as a result of its destruction and (or) secondary growth associated with mineralization. Chloritization of biotites is among the first manifestations of fluid–rock interaction in the plutons and, together with the high factor loading by lithium, suggests that alteration of primary biotite and consequent element mobilization are the primary controls of this biotite factor.

Factors 2B and 3A are heavily loaded with respect to $Al_2O_3$ and to a lesser degree $K_2O$ and $Na_2O$, respectively. These elements show a strong antipathetic relationship with respect to $SiO_2$ (i.e., quartz). We interpret these factors as reflecting the variation in the "feldspar" component of the rocks. The loading of factor 2B by $K_2O$ and Rb in the uraniferous granites reflects the predominance of muscovitization and sericitization among the alteration in these bodies, whereas the loading of factor 3A by $Na_2O$ and Sr in the stanniferous granites is a reflection of the relative importance of albitization.

Factors 4A and 4B are strongly loaded by CaO, $P_2O_5$, and F in both suites and can be interpreted as a "phosphate mineral" factor. The role of phosphorous in the uranium mineralization in the SMB is reflected in the occurrence of autunite and torbernite as important uranium minerals; as well, triplite has been reported as an accessory mineral of the tin mineralization

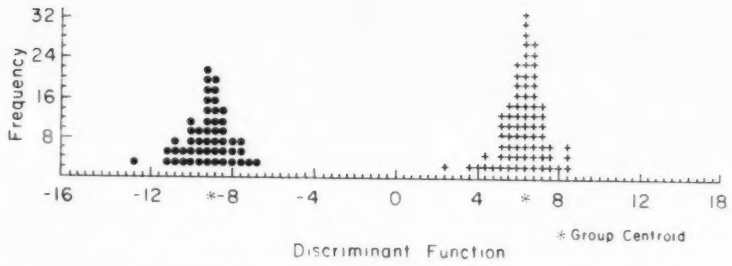


FIG. 4. Histogram of discriminant scores for 94 stanniferous (dots) and 136 uraniferous (crosses) samples from the South Mountain batholith.

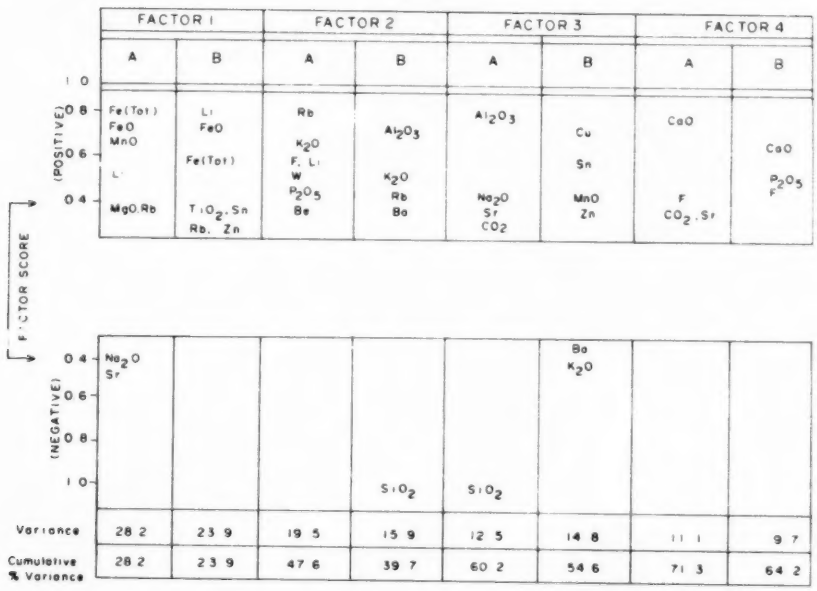


FIG. 5. The four principal factors and factor scores for different variables in the stanniferous (A) and uraniferous (B) granite samples from the South Mountain batholith.

(Chatterjee and Muecke 1982). Phosphorous, however, is also recognized as one of the important discriminators between the stanniferous and uraniferous granites as discussed below.

The remaining factors, 2A and 3B, are distinctly different from each other and are exclusive to their respective suites. Factor 2A in the stanniferous suite is heavily loaded by Rb, $K_2O$, F, Li, W, $P_2O_5$, and Be and may be called the "lithophile" factor. This association consists of elements whose high concentrations are recognized as indicators of granite specialization for tin mineralization (Tischendorf *et al.* 1978). In the uraniferous granites, factor 3B, on the other hand, is loaded with the metals Cu, Sn, Mn, and Zn. This "metallization" factor reflects the strong association of sulphides with the uraniferous shear zones and the occurrence of manganiferous shear zones in their vicinity.

We suggest that the lithophile factor recognized in the stanniferous granites reflects the close genetic link between tin mineralization and late-stage magmatic phenomena such as albitization and greisenization. The metallization factor in the uraniferous granites, on the other hand, reflects a later process during which solutions responsible for uranium mineralization might exhibit only tenuous indications of any genetic relationship to their parent bodies.

## Discussion

Chatterjee and Muecke (1982) have emphasized that in the cogenetic suite uranium increases progressively with differentiation but thorium follows two separate

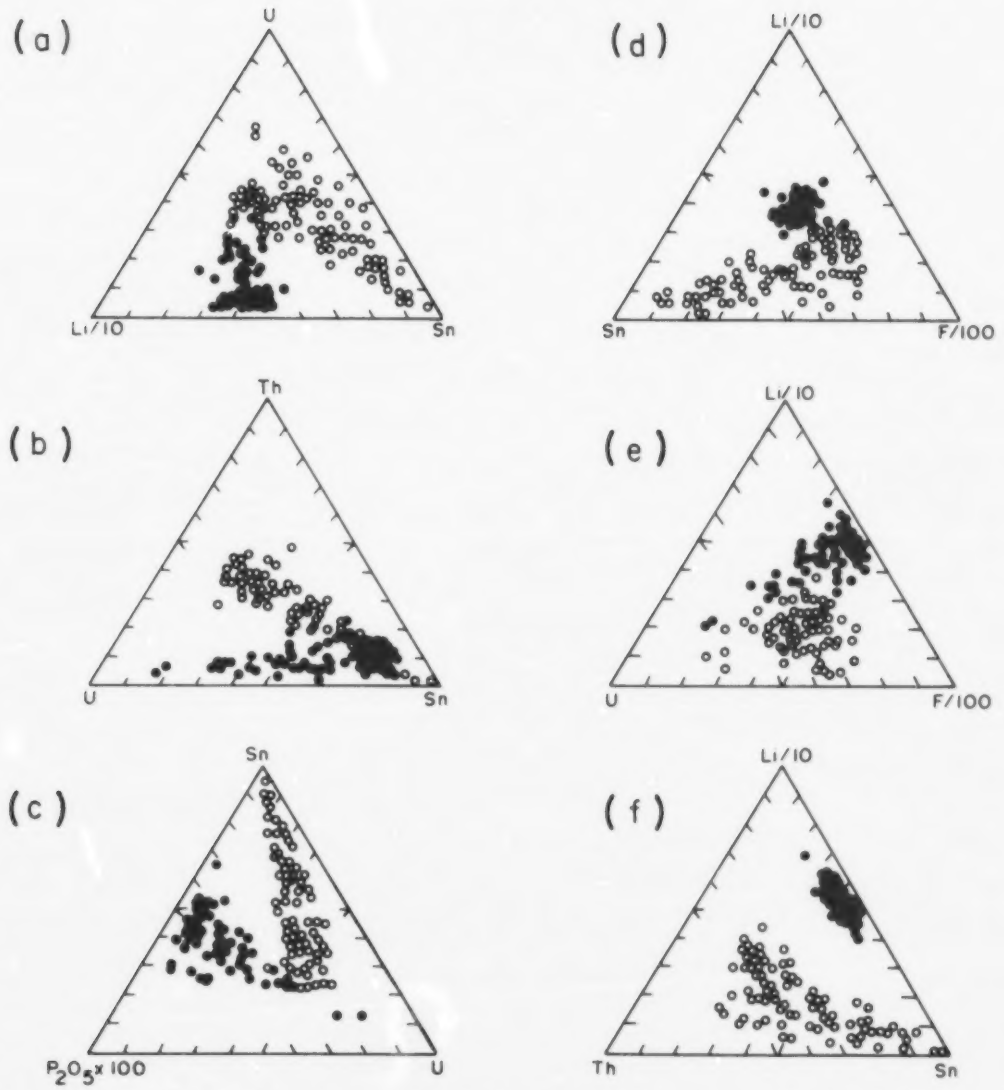


FIG. 6. Triangular variation diagrams for trace-element concentrations in the stanniferous (circles) and uraniferous (dots) suites of the South Mountain batholith.

trends. Both Th and Th/U ratios decrease with differentiation in the New Ross, Lake George, East Dalhousie, and West Dalhousie plutons, whereas both U and Th increase with differentiation in the Davis Lake and Plymouth plutons, trends that are more typical of those produced by crystal–liquid fractionation. The former Th depletion trend is accompanied by progressive depletion of Sr, Ba, rare-earth elements (REE), Sc, Zr, and Hf, and enrichment in F, Ba, Li, Rb, Cs, Ta, Sn, and U. These correlations break down in the para-intrusive specialized suites, which may display extreme enrichments of certain elements (e.g., U, Sn, Li) or depletion of others (e.g., REE, Th). Most important, however, is the observation that the REE–Th depletion in both cogenetic and para-intrusive suites is associated with uranium mineralization, and the Th-enrichment trend is associated with tin mineralization.

Although a number of significant differences in trace-element concentrations can be seen in Table 1,

there are important patterns of covariance between certain elements that must be emphasized. For example, the average concentrations of both Sn *and* U are higher in the stanniferous than the uraniferous granites, but Fig. 6 shows two separate and systematic trends for them. When plotted against Li and U (Fig. 6*a*), Sn in the stanniferous granites shows a continuous trend of enrichment from approximately equal proportions of Sn/Li/U to a complete depletion of Li and U. Uraniferous granites, on the other hand, display a trend from compositions very low in U to significant U enrichment, but not to complete depletion of Sn and Li.

Although Chatterjee and Muecke (1982) described the stanniferous granites as having a Th enrichment trend, it can be seen from Fig. 6*b* that there is essentially a trend of Sn enrichment from granites initially enriched in both Th and U. The uraniferous granites do not appear to have been Th-rich at any degree of U enrichment. In other words, each type of deposit was derived from different source rocks and these can be recognized even where no U or Sn enrichment is seen.

The very high Li concentrations of the uraniferous granites (Table 1) are emphasized in Fig. 6 *a* and *d–f*. There is evidently a complete separation between the two groups, with more or less constant Li–F–Sn or Li–Th–Sn proportions in the uraniferous granites, and consistently lower Li in the stanniferous granites, despite a large variation in Sn/F or Sn/Th ratios. These plots clearly illustrate the separate and distinctive behaviours of Sn, Li, and F in these two groups although such elements are all enriched in these and most other specialized granites.

Figure 6*e* shows the wide variation in uranium concentration with respect to Li and F in both the uraniferous and stanniferous granites, although the Li/F ratios remain relatively constant and separate for each group. Thus, despite the high Li concentration in uraniferous granites, its lack of covariation with U (a correlation coefficient of only 0.035) suggests that it was concentrated by a separate process, presumably initially magmatic although finally relating to biotite destruction as suggested by the factor analysis.

The above observations on the covariation of a range of elements with magmatic differentiation may be taken as "normal" for granitoid rocks associated with tin mineralization. This implies that such deposits, e.g., those associated with the Plymouth and Davis Lake (East Kemptville deposit) plutons, owe their origins to magmatic processes, as emphasized in the model for granophile mineral deposits outlined by Strong (1981) or Lehmann (1982). The negative correlation of Th and REE with other lithophile elements, characteristic of Nova Scotia granitoid rocks associated with uranium mineralization, is not typical of magmatic differentiation processes, and has been interpreted by Chatterjee and Muecke (1982) as resulting from mineralizing fluids, either internally generated or from hot meteoric water, interacting with the cooling granitoid rocks. However, there are systematic differences between uraniferous and stanniferous granites that are observable where there is no other evidence of mineralization, suggesting that both types are ultimately dependent on the host-rock characteristics that result from magmatic processes. The strong enrichment of the uraniferous granites in lithium, but the lack of covariation between U and Li, suggests that they were concentrated by separate processes, e.g., magmatic and hydrothermal, respectively. Although it is not clear why the uraniferous granites show this exceptional Li enrichment in the first place, it is probable that both result from initial concentration in the source rocks by sedimentary processes.

The systematic patterns of variation between U, Sn, Th, Li, and F, which are distinctly different for stanniferous and uraniferous specialized granites, allow for their recognition in rocks of economic potential that may show no other indications of mineralization, indeed, that may display "negative indication," or lower than average concentrations of Sn, U, or other lithophile elements.

Based on the data for granitoid rocks of Nova Scotia, we suggest that lithogeochemical exploration programs for U or Sn in granitoid rocks might use any number of elements or element pairs (e.g., K/Rb) to identify specialized granitoids, but that data for U, Sn, Th, Li, and F in combination are the most useful for distinction between the two.

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